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Method for electronic tuning of the read oscillation frequency of a Coriolis gyro

The invention relates to a method for electronic tuning of the frequency of the read oscillation to the frequency of the stimulation oscillation for a Coriolis gyro.

Coriolis gyros, (which are also referred to as vibration gyros) are being used to an increasing extent for navigation purposes; they have a mass system which is caused to oscillate. This oscillation is generally a superimposition of a large number of individual oscillations. These individual oscillations of the mass system are initially independent of one another and can each be regarded in an abstract form as "resonators". At least two resonators are required for operation of a vibration gyro: one of these resonators (first resonator) is artificially stimulated to oscillate, with these oscillations being referred to in the following text as a "stimulation oscillation". The other resonator (the second resonator) is stimulated to oscillate only when the vibration gyro is moved/rotated. Specifically, Coriolis forces occur in this case which couple the first resonator to the second resonator, draw energy from the stimulation oscillation of the first resonator, and transfer this energy to the read oscillation of the second resonator. The oscillation of the second resonator is referred to in the following text as the "read oscillation". In order to determine movements (in particular rotations) of the Coriolis gyro, the read oscillation is tapped off and a corresponding read signal (for example the tapped-off read oscillation signal) is investigated to determine whether any changes have occurred in the amplitude of the read oscillation which represent a measure for the rotation of the Coriolis gyro. Coriolis gyros may be in the form of both an open loop system and a closed loop system. In a closed loop system, the

amplitude of the read oscillation is continuously reset to a fixed value - preferably zero - via respective control loops.

In order to further illustrate the method of operation of a Coriolis gyro, one example of a closed loop version of a Coriolis gyro will be described in the following text, with reference to Figure 2.

A Coriolis gyro 1 such as this has a mass system 2 which can be caused to oscillate and which is also referred to in the following text as a "resonator". This expression must be distinguished from the "abstract" resonators which have been mentioned above, which represent individual oscillations of the "real" resonator. As already mentioned, the resonator 2 may be regarded as a system composed of two "resonators" (a first resonator 3 and a second resonator 4). Both the first and the second resonator 3, 4 are each coupled to a force transmitter (not shown) and to a tapping-off system (not shown). The noise which is produced by the force transmitter and the tapping-off systems is in this case indicated schematically by the noise 1 (reference symbol 5) and the noise 2 (reference symbol 6).

The Coriolis gyro 1 furthermore has four control loops:

A first control loop is used for controlling the stimulation oscillation (that is to say the frequency of the first resonator 3) at a fixed frequency (resonant frequency). The first control loop has a first demodulator 7, a first low-pass filter 8, a frequency regulator 9, a VCO (voltage controlled oscillator) 10 and a first modulator 11.

A second control loop is used for controlling the stimulation oscillation at a constant amplitude and has a second demodulator 12, a second low-pass filter 13

and an amplitude regulator 14.

A third and a fourth control loop are used for resetting those forces which stimulate the read oscillation. In this case, the third control loop has a third demodulator 15, a third low-pass filter 16, a quadrature regulator 17 and a second modulator 18. The fourth control loop contains a fourth demodulator 19, a fourth low-pass filter 20, a rotation rate regulator 21 and a third modulator 22.

The first resonator 3 is stimulated at its resonant frequency 1. The resultant stimulation oscillation is tapped off, is demodulated in phase by means of the first demodulator 7, and a demodulated signal component is passed to the first low-pass filter 8, which removes the sum frequencies from it. The tapped-off signal is also referred to in the following text as the tapped-off stimulation oscillation signal. An output signal from the first low-pass filter 8 is applied to a frequency regulator 9, which controls the VCO 10 as a function of the signal that is supplied to it such that the in-phase component essentially tends to zero. For this purpose, the VCO 10 passes a signal to the first modulator 11, which itself controls a force transmitter such that the first resonator 3 has a stimulation force applied to it. If the in-phase component is zero, then the first resonator 3 oscillates at its resonant frequency 1. It should be mentioned that all of the modulators and demodulators are operated on the basis of this resonant frequency 1.

The tapped-off stimulation oscillation signal is, furthermore, passed to the second control loop and is demodulated by the second demodulator 12, whose output is passed through the second low-pass filter 13, whose output signal is in turn supplied to the amplitude regulator 14. The amplitude regulator 14 controls the first modulator 11 as a function of this signal and of

a nominal amplitude transmitter 23 such that the first resonator 3 oscillates at a constant amplitude (that is to say the stimulation oscillation has a constant amplitude).

As has already been mentioned, movement/rotation of the Coriolis gyro 1 results in Coriolis forces - indicated by the term FCcos(1 ·t) in the drawing - which couple the first resonator 3 to the second resonator 4, and thus cause the second resonator 4 to oscillate. A resultant read oscillation at the frequency 2 is tapped off, so that a corresponding tapped-off read oscillation signal (read signal) is supplied both to the third control loop and to the fourth control loop. In the third control loop, this signal is demodulated by means of the third demodulator 15, the sum frequencies are removed by the third low-pass filter 16, and the low-pass-filtered signal is supplied to the quadrature regulator 17, whose output signal is applied to the third modulator 22 such that corresponding quadrature components of the read oscillation are reset. Analogously to this, the tapped-off read oscillation signal is demodulated in the fourth control loop by means of the fourth demodulator 19, passes through the fourth low-pass filter 20, and a correspondingly low-pass-filtered signal is applied on the one hand to the rotation rate regulator 21, whose output signal is proportional to the instantaneous rotation rate, and which is passed as the rotation rate measurement result to a rotation rate output 24, and is applied on the other hand to the second modulator 18, which resets corresponding rotation rate components of the read oscillation.

A Coriolis gyro 1 as described above may be operated not only in a double-resonant form but also in a form in which it is not double-resonant. If the Coriolis gyro 1 is operated in a double-resonant form, then the frequency 2 of the read oscillation is approximately

equal to the frequency 1 of the stimulation oscillation while, in contrast, when it is operated in a form in which it is not double-resonant, the frequency 2 of the read oscillation differs from the frequency 1 of the stimulation oscillation. In the case of double-resonance, the output signal from the fourth low-pass filter 20 contains corresponding information about the rotation rate, while, when it is not operated in a double-resonant form, on the other hand, it is the output signal from the third low-pass filter 16. In order to switch between the different double-resonant/not double-resonant modes, a doubling switch 25 is provided, which connects the outputs of the third and fourth low-pass filters 16, 20 selectively to the rotation rate regulator 21 and to the quadrature regulator 17.

When the Coriolis gyro 1 is intended to be operated in a double-resonant form, the frequency of the read oscillation must be tuned - as mentioned - to the frequency of the stimulation oscillation. This may be achieved, for example, by mechanical means, in which material is removed from the mass system (to the resonator 2). As an alternative to this, the frequency of the read oscillation can also be set by means of an electrical field, in which the resonator 2 is mounted such that it can oscillate, that is to say by changing the electrical field strength. It is thus possible to electronically tune the frequency of the read oscillation to the frequency of the stimulation oscillation during operation of the Coriolis gyro 1, as well.

The object on which the invention is based is to provide a method by means of which the frequency of the read oscillation in a Coriolis gyro can be electronically tuned to the frequency of the stimulation oscillation.

This object is achieved by the method as claimed in the features of patent claim 1. The invention furthermore provides a Coriolis gyro as claimed in patent claim 10. Advantageous refinements and developments of the idea of the invention can be found in the respective dependent claims.

According to the invention, in the case of a method for electronic tuning of the frequency of the read oscillation to the frequency of the stimulation oscillation in a Coriolis gyro, the resonator of the Coriolis gyro has a disturbance force applied to it such that a) the stimulation oscillation remains essentially uninfluenced, and b) the read oscillation is changed such that a read signal which represents the read oscillation contains a corresponding disturbance component, wherein the frequency of the read oscillation is controlled such that any phase shift between a disturbance signal which produces the disturbance force and the disturbance component which is contained in the read signal is as small as possible.

In this case, the wording "resonator" means the entire mass system (or a part of it) which can be caused to oscillate in the Coriolis gyro - that is to say that part of the Coriolis gyro which is annotated with the reference number 2.

A significant discovery on which the invention is based is that the "time for disturbance to pass through", that is to say an artificial change to the read oscillation resulting from the application of appropriate disturbance forces to the resonator, the resonator, that is to say the time which passes from the effect of the disturbance on the resonator until the disturbance is tapped off as part of the read signal, is dependent on the frequency of the read oscillation. The shift between the phase of the

disturbance signal and the phase of the disturbance component signal which is contained in the read signal is thus a measure of the frequency of the read oscillation. It can be shown that the phase shift assumes a minimum when the frequency of the read oscillation essentially matches the frequency of the stimulation oscillation. If the frequency of the read oscillation is thus controlled such that the phase shift assumes a minimum, then the frequency of the read oscillation is thus at the same time essentially matched to the frequency of the stimulation oscillation.

The significant factor in this case is that the disturbance forces on the resonator change only the read oscillation, but not the stimulation oscillation. With reference to Figure 2, this means that the disturbance forces act only on the second resonator 4, but not on the first resonator 3.

The disturbance force is preferably produced by a disturbance signal which is supplied to appropriate force transmitters, or is added to signals which are supplied to the force transmitters. By way of example, a disturbance signal can be added to the respective control/reset signals for control/compensation of the read oscillation, in order to produce the disturbance force.

The disturbance signal is preferably an alternating signal, for example a superimposition of sine-wave signals and cosine-wave signals. This disturbance signal is generally at a fixed disturbance frequency, so that the disturbance component of the tapped-off read oscillation signal can be determined by means of an appropriate demodulation process, which is carried out at the said disturbance frequency.

The method described above can be used both for an open loop and for a closed loop Coriolis gyro. In the latter case, the disturbance signal is preferably added to the respective control/reset signals for control/ compensation of the read oscillation. By way of example, the disturbance signal can be added to the output signal from the quadrature control loop, and the disturbance component can be determined from a signal which is applied to a quadrature regulator in the quadrature control loop, or is emitted from it. Furthermore, it is possible to add the disturbance signal to the output signal from the rotation rate control loop, and to determine the disturbance component from a signal which is applied to a rotation rate regulator in the rotation rate control loop, or is emitted from it. The expression "read signal" covers all signals which are described in this paragraph and from which the disturbance component can be determined. It can also mean the tapped-off read oscillation signal.

The frequency of the read oscillation, that is to say the force transmission of the control forces which are required for frequency control, is in this case controlled by controlling the intensity of an electrical field in which a part of the resonator oscillates, with an electrical attraction force between the resonator and an opposing piece, which is fixed to the frame and surrounds the resonator, preferably being non-linear.

The invention furthermore provides a Coriolis gyro which has a rotation rate control loop and a quadrature control loop and is characterized by a device for electronic tuning of the frequency of the read oscillation to the frequency of the stimulation oscillation. The device for electronic tuning in this case has:

- a disturbance unit which passes a disturbance signal to the rotation rate control loop or to the quadrature control loop,
- a disturbance signal detection unit, which determines a disturbance component which is contained in a read signal (which represents the read oscillation) and has been produced by the disturbance signal, and
- a control unit, which controls the frequency of the read oscillation such that any phase shift between the disturbance signal and the disturbance component which is contained in the read signal is as small as possible.

The disturbance unit preferably passes the disturbance signal to the rotation rate control loop, and the disturbance signal detection unit determines the disturbance component from a signal which is applied to a rotation rate regulator in the rotation rate control loop, or is emitted from it. A further alternative is for the disturbance signal to be passed by the disturbance unit to the quadrature control loop, with the disturbance signal detection unit then determining the disturbance component from a signal which is applied to a quadrature regulator in the quadrature control loop, or is emitted from it.

One exemplary embodiment of the invention will be explained in more detail in the following text with reference to the accompanying figures, in which:

Figure 1 shows the schematic design of a Coriolis gyro which is based on the method according to the invention; and

Figure 2 shows the schematic design of a conventional Coriolis gyro.

First of all, one exemplary embodiment of the method according to the invention will be explained in more detail with reference to Figure 1. In this case, parts and/or devices which correspond to those in Figure 2 are identified by the same reference symbols, and will not be explained once again.

A Coriolis gyro 1' is additionally provided with a disturbance unit 26, a first demodulation unit 27, a read oscillation frequency regulator 28, a read oscillation modulation unit 29, a second demodulation unit 30 and a modulation correction unit 31.

The disturbance unit 26 produces a first disturbance signal, preferably an alternating signal at a frequency mod, which is added to the output signal from a rotation rate regulator 21 (that is to say at the force output from the rotation rate control loop). The collated signal which is obtained in this way is supplied to a modulator 18 (second modulator), whose corresponding output signal is applied to the resonator 2 by means of a force transmitter (not shown). The alternating signal is additionally supplied to the first demodulation unit 27.

The tapped-off read oscillation signal is demodulated by a fourth demodulator 19, the output signal from the fourth demodulator being applied to a fourth low-pass filter 20, whose output signal is supplied to a rotation rate regulator 21. An output signal from the rotation rate regulator 21 is supplied both to the second modulator 18 and to the first demodulation unit 27, which demodulates this signal based on the modulation frequency mod which corresponds to the frequency of the alternating signal which is produced by the disturbance unit 26 and the disturbance component or the alternating signal which represents the disturbance produced by the disturbance unit 26 is thus determined. In particular, the first demodulation

unit 27 determines the phase of the disturbance component signal contained in the read signal, and compares this with the phase of the disturbance signal which is produced by the disturbance unit 26. The phase shift calculated in this way is supplied to the read oscillation frequency regulator 28, which adjusts the frequency of the read oscillation such that the phase shift is a minimum. In order to regulate the phase shift at a minimum, the electronically tunable frequency of the read oscillation is modulated with a second disturbance signal ω2-Mod by the read oscillation modulation unit 29. This results in the phase shift being varied in accordance with this second disturbance signal. The phase shift from the first demodulation unit 27 is now demodulated corresponding to the second disturbance signal ω2-Mod. If the phase shift from the first demodulation unit 27 is substantially a minimum, then the signal at the input of the read oscillation frequency regulator 28 is essentially zero. If, in contrast, the phase shift is not a minimum, then this results in a signal other than zero at the input of the read oscillation frequency regulator 28 and with a corresponding mathematical sign, so that the read oscillation frequency regulator 28 minimizes the phase shift by means of the electronic frequency control. When a minimum such as this has been reached, then the frequencies of the stimulation oscillation and of the read oscillation essentially match.

As already mentioned, and as an alternative to this, the alternating signal which is produced by the disturbance unit 26 can also be added to an output signal from the quadrature regulator 17. In this case, the signal which is supplied to the first demodulation unit 27 would be tapped off at the input or output of the quadrature regulator 17.

Furthermore, in principle, it is possible to feed the disturbance signal into the quadrature control loop/rotation rate control loop at any desired point (not only directly upstream of the second or third modulator 18, 22), that is to say at any desired point between the point at which the read oscillation is tapped off and the second or third modulator 18, 22.

Once the Coriolis gyro 1' has been switched on, it is advantageous to set the modulation frequency mod of the alternating signal to a high value in order to quickly achieve coarse control of the read oscillation frequency. It is then possible to switch to a relatively low modulation frequency mod, in order to precisely set resonance of the read oscillation. Furthermore, the amplitude of the modulation frequency mod can be greatly reduced a certain time after stabilization of the rotation rate regulator 21 and/or of the quadrature regulator 17.

In principle, all the modulation processes can also be carried out on the basis of band-limited noise. This means that all the alternating signals described above (the first disturbance signal ωmod and the second disturbance signal ω2-Mod) can be replaced by corresponding noise signals, with the corresponding demodulation processes in this case being carried out on the basis of cross-correlation, that is to say on the basis of a correlation between the noise signals and the read signal, which contains noise components (disturbance components) produced by the noise signals.

In the case of a second alternative method for electronic tuning of the frequency of the read oscillation to the frequency of the stimulation oscillation in a Coriolis gyro, a disturbance force is applied to the resonator of the Coriolis gyro in such a way that a) the stimulation oscillation remains essentially uninfluenced, and b) the read oscillation

is changed such that a read signal which represents the read oscillation contains a corresponding disturbance component, wherein the frequency of the read oscillation is controlled such that the magnitude of the disturbance component which is contained in the read signal is as small as possible.

A significant discovery on which the invention is based is that an artificial change to the read oscillation in the rotation rate channel or quadrature channel is visible to a greater extent, in particular in the respective channel which is orthogonal to this, the less the extent to which the frequency of the read oscillation matches the frequency of the stimulation oscillation. The "penetration strength" of a disturbance such as this to the tapped-off read oscillation signal (in particular to the orthogonal channel) is thus a measure of how accurately the frequency of the read oscillation is matched to the frequency of the stimulation oscillation. Thus, if the frequency of the read oscillation is controlled such that the penetration strength assumes a minimum, that is to say such that the magnitude of the disturbance component which is contained in the tapped-off read oscillation signal is a minimum, then the frequency of the read oscillation is thus at the same time essentially matched to the frequency of the stimulation oscillation.

The significant factor in this case is that the disturbance forces on the resonator change only the read oscillation, but not the stimulation oscillation. With reference to Figure 2, this means that the disturbance forces act only on the second resonator 4, but not on the first resonator 3.

In a third alternative method for electronic tuning of the frequency of the read oscillation to the frequency of the stimulation oscillation in a Coriolis gyro, the

resonator of the Coriolis gyro has a disturbance force applied to it such that a) the stimulation oscillation remains essentially uninfluenced and b) the read oscillation is changed such that a read signal which represents the read oscillation contains a corresponding disturbance component, with the disturbance force being defined as that force which is caused by the signal noise in the read signal. The frequency of the read oscillation is in this case controlled such that the magnitude of the disturbance component which is contained in the read signal, that is to say the noise component, is as small as possible.

The word "resonator" in this case means the entire mass system which can be caused to oscillate in the Coriolis gyro - that is to say that part of the Coriolis gyro which is identified by the reference number 2. The essential feature in this case is that the disturbance forces on the resonator change only the read oscillation, but not the stimulation oscillation. With reference to Figure 2, this would mean that the disturbance forces acted only on the second resonator 4, but not on the first resonator 3.

A significant discovery on which the third alternative method is based is that a disturbance signal in the form of signal noise, which occurs directly in the tapped-off read oscillation signal or at the input of the control loops (rotation rate control loop/quadrature control loop) can be observed to a greater extent in the tapped-off read oscillation signal after "passing through" the control loops and the resonator, the less the extent to which the frequency of the read oscillation matches the frequency of the stimulation oscillation. The signal noise, which is the signal noise of the read oscillation tapping-off electronics or the random walk of the Coriolis gyro, is applied, after "passing through" the control loops, to the force transmitters and thus produces corresponding

disturbance forces, which are applied to the resonator and thus cause an artificial change in the read oscillation. The "penetration strength" of a disturbance such as this to the tapped-off read oscillation signal is thus a measure of how accurately the frequency of the read oscillation is matched to the frequency of the stimulation oscillation. Thus, if the frequency of the read oscillation is controlled such that the penetration strength assumes a minimum, that is to say the magnitude of the disturbance component which is contained in the tapped-off read oscillation signal, that is to say the noise component, is a minimum, then the frequency of the read oscillation is at the same time thus matched to the frequency of the stimulation oscillation.

The first method according to the invention which was described for electronic tuning of the read oscillation frequency can be combined as required with the second alternative method and/or with the third alternative method. For example, it is possible to use the method described first while the Coriolis gyro is being started up (rapid transient response), and then to use the third alternative method (slow control process) in steady-state operation. Specific technical refinements as well as further details relating to the methods can be found by those skilled in the art in the patent applications "Verfahren zur elektronischen Abstimmung der Ausleseschwingungsfrequenz eines Corioliskreisels", [Method for electronic tuning of the read oscillation frequency of a Coriolis gyro], LTF-190-DE and LTF-192-DE from the same applicant, in which, respectively, the second alternative method and the third alternative method are described. The entire contents of the patent applications LTF-190-DE/ LTF-192-DE are thus hereby included in the description.